5 739200

1

(B) 739 200

(6) SYSTEMS ENGINEERING,

(10) by Alexander W. Boldyreff,
~~Mathematics Division~~
~~The RAND Corporation~~

P-537

16 June 1954

SUMMARY

This paper deals with the problem of optimum design and operation of complex systems.

The present text has been prepared primarily for presentation at the Joint Western Region ASQC-ATC Conference to be held in San Diego, August 9-10, 1954.

In an expanded and revised form the material of this paper will be used in the introductory chapter of a book on Systems Engineering, the manuscript of which is now in preparation.

1. The purpose and the scope of systems engineering
2. Its nature.
3. The relation between operating systems and their mathematical models.
4. Methods and tools, old and new.
5. The problem of selection and efficient utilization of systems engineering personnel, and
6. Some dangers and pitfalls to be avoided.

The Purpose and the Scope.

During World War II the British developed the conception of Operations Research as the application of the basic scientific methods of observation, measurement, classification, comparison, correlation, and analysis to the selection of means for attaining, with the least expenditure in effort and time, the maximum operational effect which could be extracted from the available or potentially available resources in material and personnel.

The operations researcher was visualized as requiring dual ranges of knowledge; a wide and fairly detailed knowledge of the technical capabilities and limitations of the equipment in use or capable of development, and a close personal knowledge of the working environment in which it was to be used and of the people who were to use it. This job was to look for quantitative data, and to isolate the influence of the planned variations in each of the determining parameters on system performance.

The purpose of operations research was to examine quantitatively whether the user organization was getting from the operation of its equipment the best attainable contribution to its over-all objective, to determine the dominant factors governing the results attained, to recommend changes in equipment or method that could be reasonably expected to improve these results at a minimal cost in effort and time, and to predict the degree to which variations in the short range objectives are likely to contribute to a more economical attainment of the over-all long range objectives.

These methods originally were developed in Great Britian and the United States to deal with strictly military problems. In this application they were most successful.

There is no doubt that the same techniques may be used equally well in peacetime for the study and improvement of such operations as manufacturing, distribution, communication, transportation, agriculture, etc. In fact, these methods should be applicable to the operation of any large organization or system which performs an essentially repetitive process, expressible in quantitative terms.

The Nature of the Activity.

To be more than a purely academic activity, Systems Engineering must be first of all based on a firm foundation of empirical fact. It must be realistic. It must ultimately lead to conclusions and recommendations resulting in constructive action. It must be practical.

The most important primary function of Systems Engineering is the recognition of the real problems and concentration first on those problems that are both important and capable of a quick solution.

It must necessarily begin with a critical examination of the objectives which the system tries to achieve, and a detailed study of the alternative means and conditions for reaching these objective.

Are the objectives really necessary?

Are they technically attainable?

After this critical scrutiny, each of the following steps are employed:

1. System description in terms of essential parameters. Of the many parameters defining the system, is it possible to isolate a few that are of primary importance and to prove that others are of little or no significance?

   As an example of what can be accomplished in this direction, A. W. Swan, in a paper entitled "Some Post-War Developments in Operational Research in Great Britain," cites a study of a certain industry where, of some 80 variables, it was found that only 3 mattered to an important extent.
2. Construction of an efficient Mathematical Model and its analysis.
3. Comparison of the theoretical predictions from the analysis of the model with the factual observations in the systems. Perfection of the Model.
4. System optimization through changes dictated by the analysis of the model.

Relation between the Operating System and its Mathematical Model.

Mathematical analysis can never be applied directly to a given physical system or situation. It is always necessary to construct first a mathematical model of the physical system by a process of abstraction or idealization. Logically, this is equivalent to selection of a set of postulates or hypotheses in terms of which the mathematical model is defined.

Mathematical Analysis, applied to this set of postulates, serves then to deduce all significant consequences implicit in the defining hypotheses of the mathematical model.

How accruately such an abstract model can describe the actual physical system, and how well deductions from the mathematical model can serve to predict the course of events (or the behaviour) for an actual physical system will depend completely on the choice of the hypothetical basis of the model used to represent the system. And the only certain test of the success of representation of a real physical system by means of a mathematical model is a detailed comparison of the predictions deduced theoretically from the model with the results measured experimentally in the system.

Every system has its origin in the formulation of characteristics of the systems, dictated by the objectives which the system is desired to attain. The research phase of the evolution of the system concerns itself with the investigation of all possible and reasonable means of accomplishing the task set for the system. Development narrows the field of possibilities to those ways of accomplishing the task which are practical. Test serves to verify performance and to pin-point sources of failure. Design and production choose and manufacture the system which is capable of reliably and economically fulfilling its required task.

Every system can be described in terms of its characteristic parameters such as its physical make-up, its size and shape, weight, function, and performance, reliability, requirements for maintenance and logistic support, including personnel and their training, environmental conditions, cost, etc. These parameters are not independent variables. Thus, an increase in performance generally implies a decrease in reliability and an increase in cost and requirements for maintenance and logistic support. Therefore, the problem of systems engineering is one of complete optimization. Such complete optimization is impossible without a firm foundation of empirical fact on which realistic hypotheses can be based leading to the formulation of efficient mathematical models. Mathematical analysis of such models would then yield deductions in terms of which the behavior of the system can be predicted. However, unless such predictions are checked by actual test or experiment no complete reliance can be placed in them. At best, their value is purely tentative, subject to verification when factual data become available. It is this "closed loop" philosophy that lies at the basis of Systems Engineering. The comparison of the predicted behavior, deduced from the mathematical model with the actually observed behavior of the real system provides "the error signal" which is used to continuously modify the model. When the model has thus been sufficiently perfected, it yields recommendations for changes in the system or its method of operation. The modified system is re-examined and described in terms of a new model. This cycle is then repeated over and over again until optimum system operation, consistent with practical considerations, is achieved.

In the use of mathematical model the key to success is simplicity. Only those assumptions are made in which we have a high degree of confidence. It is true that only limited descriptions of the system and limited predictions of its behavior will be initially possible. But, at least as time goes on, it will not be necessary to discard the model or revise radically our original conclusions. Instead, through the operation of the closed-loop system of analysis, it will be possible to expand and refine the model, and to increase both the detail and the accuracy with which the behavior of the system can be predicted.

Two historical examples will be cited to support this position.

The first is Euclidean Geometry conceived as an abstract model of physical space. The other—Newton's model of the solar system explaining the observed motions of the planets.

<u>Symbolic Representation of a System</u>.

System Objectives → Operating System → System Performance

Material Equipment

Operating Procedure

Operating Personnel

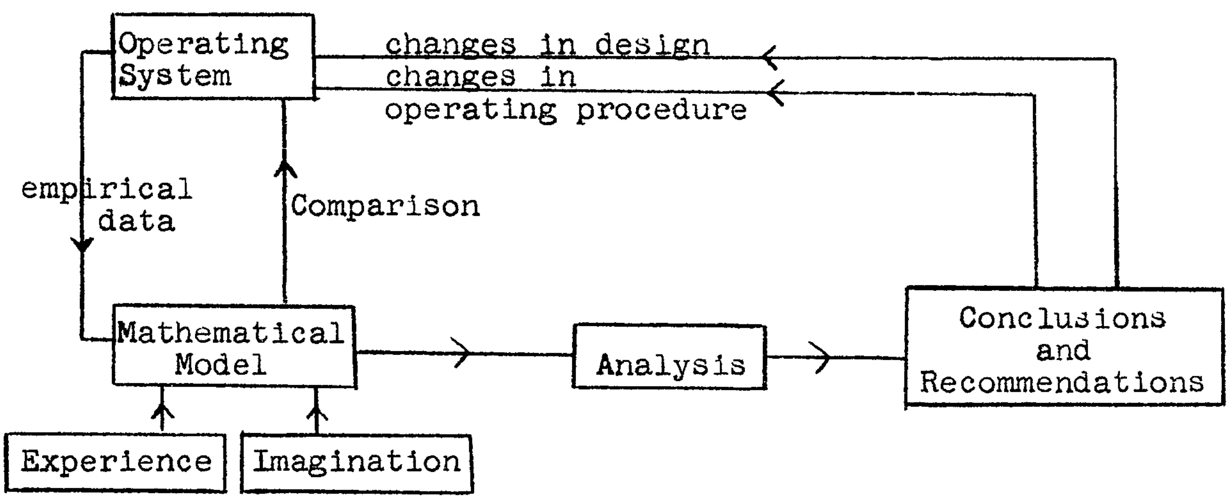
Operating Environment

Logistic Support

The recommendations derived from the analysis of the model lead to changes in the system, resulting from the changes in the equipment design or operating procedures or both. As the system changes corresponding changes are incorporated in the model.

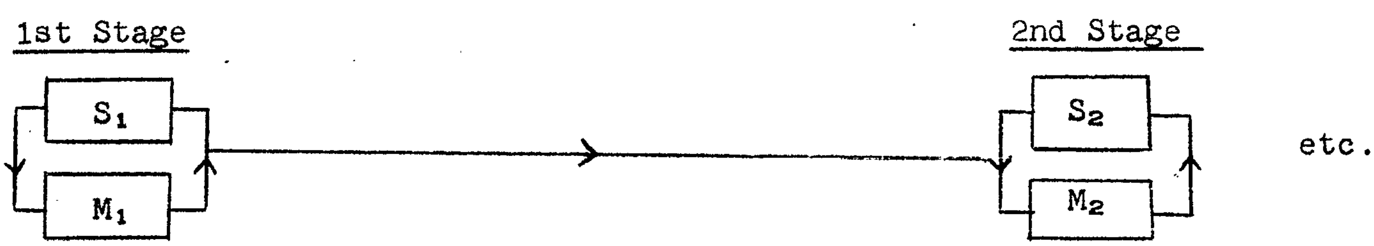
This situation can be graphically represented as follows:

The Closed Loop Concept of Systems Engineering



The continuous interaction between the changing system and its model may be shown as follows:

The Changing System and Model



It is the ideal aim of Systems Engineering that the sequences S_i and M_i both should converge, the first to an optimal operating system, the second to a "perfect" mathematical model of the former.

Methods and Tools

Systems Engineering employs all of the traditional tools of Mathematics and on occasion fashions new ones.

The following outline therefore is merely of those items that deserve special emphasis.

A. Collection and Analysis of Data.

Frequently collection of data alone, and its orderly arrangement in the form of tables and graphs will point to important relationships and problems, as well as suggest an efficient model.

The following are most important at this stage.

1. Numerical Mathematical Analysis.
2. Statistics and Probability Theory.
3. Sampling Techniques.
4. Tests of Confidence and Significance.
5. Multivariate Analysis.

B. Analysis of Models.

1. The a-Priori Method.

Here a highly simplified arbitrary model is assumed and the general solution is sought.

The tools most suited for the task are systems of differential equations and their solutions.

A good example of the use of the a-priori approach is the celebrated Lanchester's N^2 law.

2. The Variational Techniques.

Assume a system yield, generally a multi-dimensional vector, which is a function (generally of an unknown form) of the system parameters, and study the equations of the type

$$d\overline{Y} = \sum \frac{\partial \overline{Y}}{\partial x_i} dx_i \quad .$$

The partial derivatives involved are either found firectly, or deduced indirectly.

3. New Techniques.

Of the new techniques recently developed in connection with systems problems the following are most worthy of note:

(a) Linear Programming

(b) Theory of Games

(c) The Monte Carlo techniques

Selection and Utilization of Personnel

Selection

Waldo H. Kliever, Director of Research, Minneapolis-Honeywell Regulator Co., points out that "It is generally better not to do something than to do it with employees who are unqualified and therefore incapable of performing the work."

This is particularly true in selecting personnel for Systems Engineering.

The following qualifications are suggested:

1. Intellectual Integrity and Courage of Convictions.

2. Originality and Vision

3. Technical competence and Maturity in the sense of sound training and good understanding of the fundamentals of Mathematics, Physics, Chemistry, and Engineering.

4. Scientific Curiosity.

5. Energy.

6. Practical Outlook

7. Cooperative Attitude

8. Ability to translate results of highly technical analyses into intelligent non-technical terms.

Utilization

To function effectively good Systems Engineering personnel require favorable working conditions.

The minimum of these is as follows:

1. Freedom to define problems. (Quote from Mees)

2. Provisions for direct liaison with operating personnel at all levels.

3. Outside liaison with organizations and agencies concerned with related problems.

4. Access to top executive level.

Dangers and Pitfalls

1. Tendency of the incompetents and the unscrupulous to rush into this new field of activity.

2. Lack of understanding of the activity and what it can do by the executives.

3. Perversion of systems analysis to promotional uses.

mhb